IMD in Digital Receivers

Performance limitations of receivers with the A/D converter at the antenna – how to measure and work around them.

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Today, most receivers have an A/D converter at some point in the signal path because digital technology can provide better filters at lower cost compared to analog technologies. The A/D converters gradually move nearer the antenna and digital technology takes over a larger fraction of all the filtering work. Someday receivers will be completely digital and sample directly at the signal frequency — at least for HF bands. Sampling directly at the signal frequency is already possible today with amateur equipment. The first commercially available equipment is the SDR-14 from RFSPACE. This article highlights the problems of characterizing this new class of radio receivers.

Standard methods of characterizing performance in terms of third-order intercept and intermodulation-free dynamic range fail badly and cannot be used at all to give an adequate representation of how well these new receivers perform as compared to conventional radios when used on the same antenna with real signals. New ways of doing measurements are called for, and this article is intended to shed some light on the problems of measurement and on the methods we can use to improve performance by adding preselectors and reducing out-of-band signals. The SDR-14 is used as the example, but all the problems are inherent in the technology. Digital technology is developing rapidly; better A/D converters become available and performance will improve drastically in the future but still the problems of properly characterizing a radio receiver will remain.

Practical Consequences of Dynamic Range Limitations in the SDR-14

Look at Figure 1. This computer screen capture shows two waterfall graphs taken from the 40-m band. The lower one is made with the SDR-14 hardware while the upper one is made with a Delta 44 soundcard connected to WSE converters that bring the signals down to baseband I and Q. The waterfalls are produced with two instances of Linrad running simultaneously in the same computer under *Gnome*, a graphical user interface for Linux. The two systems are connected to the same antenna and the noise figure is made equal by having a 1-dB attenuator at the input of the SDR-14. See Figure 2. A preselector with adequate dynamic range and a gain figure of 26 dB followed by a stepped attenuator is placed between a simple wire antenna and a –3-dB hybrid. The Delta 44 sampling speed is 96 kHz and therefore its waterfall only covers 96 kHz of the 40-m band. The SDR-14 always samples at 66.667 MHz but its decimation chip is set to deliver the baseband I and Q at a sampling rate of 189.4 kHz, and therefore it shows about twice as wide a spectrum. A quick glance at the lower part of Figure 1 shows that there are many false signals in the SDR-14 spectrum. They occur at every 5 kHz and it is pretty obvious that they originate in some kind of nonlinearity that mixes the AM broadcast carriers of the 40-m band with each other, producing high-order intermodulation products — or at least spurious signals that occur at frequencies where intermodulation products would be expected.

Now look at Figure 3. That image was made a few minutes later than Figure 1. The only difference is that the stepped attenuator is set for much stronger signals and that the color scale of the waterfalls is changed accordingly. Both receivers see 40 dB more signal. Note that the "intermodulation" products have disappeared completely. There is not the slightest trace of the nonlinearities when the SDR-14 is fed with strong enough signals! It is obvious that the mechanism producing the false signals is not what we normally call intermodulation and characterize with an IP3 number. The SDR-14 is an excellent receiver provided it is preceded by a suitable preselector that removes most of the HF signals outside the band of interest and amplifies what passes the filter to a level close to the maximum level the unit can handle. There is an LED on the

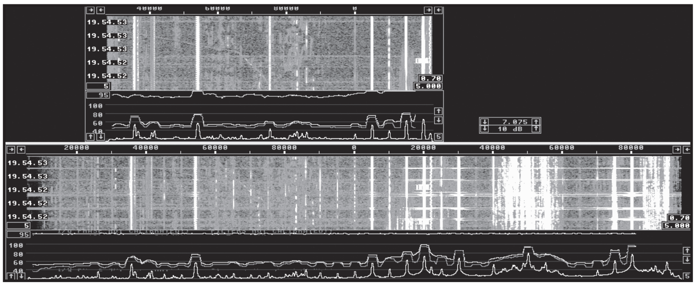
Figure 1 — The top screen capture is made with a Delta 44 soundcard connected to WSE converters that bring the signals down to baseband I and Q. The lower screen capture is made with the SDR-14 hardware.

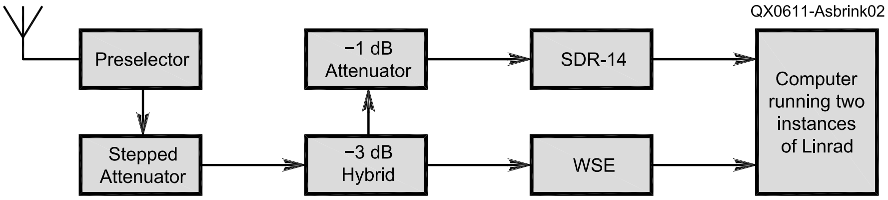

Figure 2 — Test setup for the simultaneous test of two hardware systems on a single computer running two instances of *Linrad*.

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SDR-14 showing if too much gain is applied. More color images and detailed information about this real life test can be found on the Internet.[1]

The Two-Tone Test Applied to the SDR-14

The level of the third-order intermodulation products do not follow the third-order law at all. It is absolutely unacceptable to attribute a third-order intercept point (IP3) to this receiver. The performance has to be characterized with some other figure of merit. The measurement, however, is the same. Feed two equally strong signals simultaneously into the unit and measure the level of the signals at the intermodulation frequencies. The measurements have to be done at many signal levels in order to produce the function intermodulation versus input level. Such functions in steps of 5 dB are plotted in Figure 4 for several orders of the "intermodulation product." The mechanism is not ordinary intermodulation and the signals at frequencies corresponding to different orders of intermodulation do not have amplitude relationships that bear the slightest resemblance to what one would see in an analog receiver.

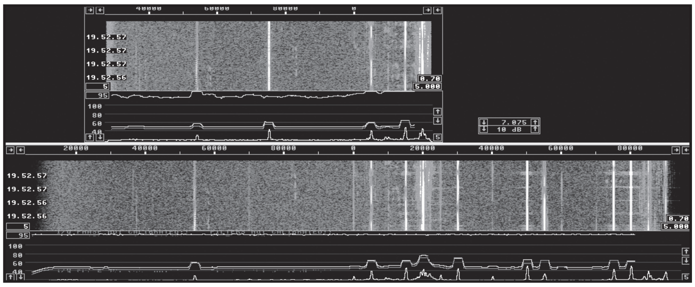

Figure 3 — The screen captures here are made the same way as those of Figure 1. The only difference is that the stepped attenuator is set for much stronger signals and that the color scale of the waterfalls is changed accordingly. Both receivers see 40 dB more signal. Note that the "intermodulation" products have disappeared completely.

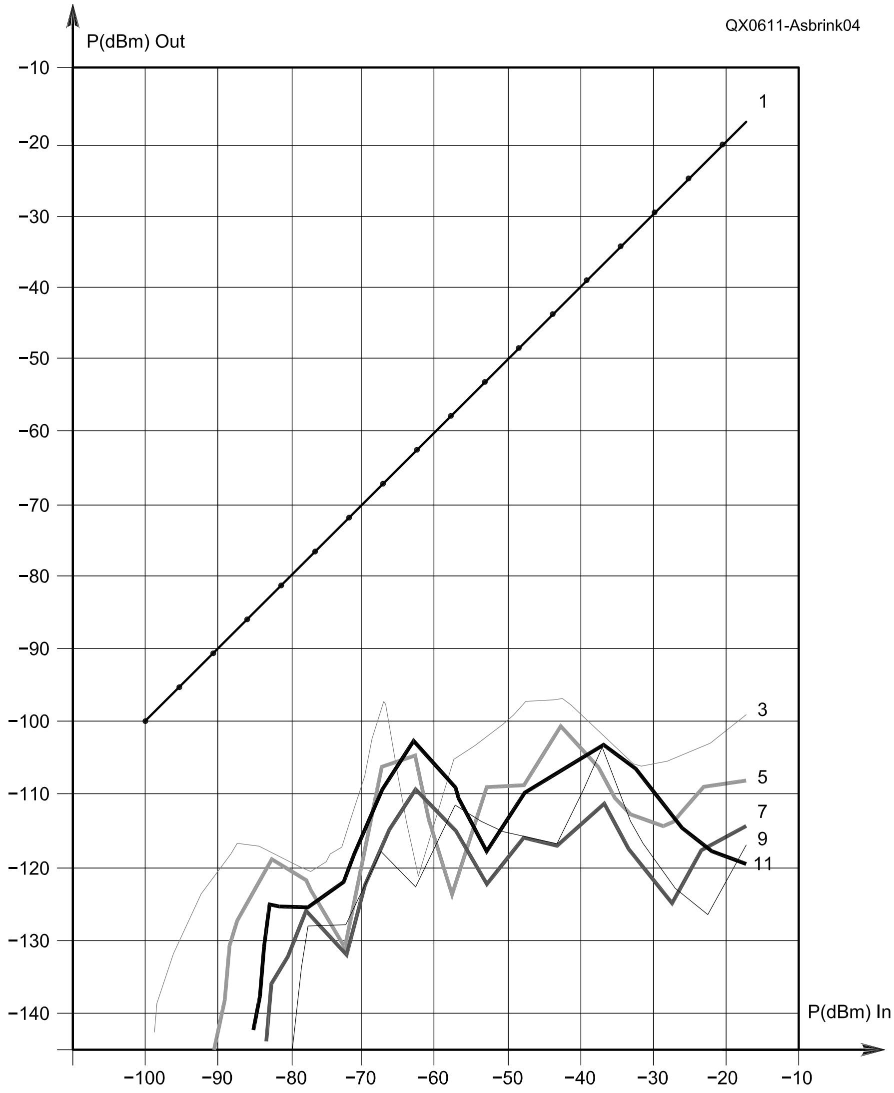

Figure 4 — Two-tone test for the SDR-14 using the 0.1 to 30 MHz input. Third-order "intermodulation" is at about –100 dBm, independent of the test signal level. Higher order interference, IM5, IM7, IM9 and IM11 are at similar power levels.

The curves in Figure 4 do not allow an IP3 to be determined, but they do allow a determination of the third-order intermodulation-free dynamic range. Two input signals at –17.5 dBm produce IM3 at –99.1 dBm. The best two-tone intermodulation-free dynamic range is thus about 82 dB, and the noise floor would have to be put at about –100 dBm at 500 Hz bandwidth. This is 35 dB above the internal noise floor of the SDR-14 itself.

–174 dBm (room temperature) + 12dB (SDR-14 noise figure) + 27 dB (500 Hz bandwidth) = –135 dBm (noise floor power of SDR-14) This result is well in line with the observations made on real life signals (see Note 1). Table 1 shows the measured data.

Dithering

The interference observed in a two-tone test is produced by the addition of an error signal that depends on the digital value of the A/D output. It does not matter whether the reason is limited accuracy of the A/D process or whether the reason is pickup of a voltage from one of the lines of the digital data bus. The error will occur periodically and therefore it will generate periodical signals. In a two-tone test, such signals will look like intermodulation. Dithering is often used to destroy the periodicity of the error signal. By adding noise, one can force the errors to occur at random times and thereby smear out the signal energy so no false signal is created. As a consequence there will of course be some degradation of the noise floor.

When adding wideband noise for dithering, it is a good idea to use a notch filter that will not allow any noise at the signal frequency to reach the A/D converter. When adding wideband noise at a power level 6 dB below the level where the saturation indicator flashes occasionally, the noise floor only increases by 3 dB in the selected passband. The false signals are drastically reduced, however, as can be seen in Figure 5. Table 2 shows the measured data.

With the test tones at –32 dBm, the only observable interference signal is at –130 dBm,

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[1] **www.sm5bsz.com/digdynam/practical.htm**

which is only 2 dB above the intrinsic noise floor power of the dithered SDR-14 unit. The best two-tone, third-order, intermodulation-free dynamic range is thus improved from 82 dB to 98 dB by dithering, with notched white noise.

Dithering does not require random signals, however. Any signal outside the passband can be used. If the dithering signal is a sine wave, the spurs will move to other frequencies that correspond to mixing products between the dither signal and its overtones, and the test signals. To smear out such signals one can frequency modulate a sine wave with a low frequency sine wave. Figure 6 shows the performance of an SDR-14 on 10.7 MHz, when dithered by a frequency-modulated sine wave at 7.22 MHz. The power of the dithering signal was –20 dBm, about 9dB below the point of saturation. The modulation frequency was 1 kHz and the frequency swing about 200 kHz. The higher-order intermodulation products are smeared out over many MHz and no low-order spur is visible within about 190 kHz on the computer screen. The frequency modulated sine wave makes a better dithering signal than random noise. It sweeps nearly the full range of the A/D converter continuously while the white noise only occasionally reaches full amplitude and sometimes has a very low amplitude for quite some time. The noise floor is degraded by 4 dB, because there is more noise produced on the digital data bus, causing the analog input to pick up a little more. The false signals of higher order have disappeared completely and the third-order signal behaves as if the SDR-14 were an analog radio with an IP3 of +21 dBm and a noise figure of 15 dB. See Figure 6. Table 3 shows the measured data.

The third-order intermodulation seen here originates in the preamplifier. By sending the test signal into the direct input, one can avoid the preamplifier and the low-pass filter inside the SDR-14. With a dithering signal of –3 dBm at 7.22 MHz and two test tones at 10.7 MHz, each at –5 dBm, one finds the third-order signals at –95 dBm. Higher-order signals are visible at a similar level. The noise figure of this input is about 30 dB without any signals and about 36 dB with all three signals present. An RF amplifier that could drive the A/D converter without degrading the dynamic range much would have to have an output IP3 well above

Table 2

Power in dBm for signals of order N

N: 1	3	5	7
–22.5	–110.1	–127	—
–27.6	–119.7	–128	–132
–32.6	–130	—	—
–37.5	–132	—	—

Table 1

Power in dBm for signals of order N

N: 1	3	5	7	9	11
–17.5	–99.1	–107.7	–114.5	–117.4	–118.9
–22.5	–103.0	–108.7	–117.1	–126.4	–117.2
–27.4	–104.8	–114.2	–113.2	–121.8	–124.5
–32.4	–106.4	–113.0	–106.2	–108.8	–118.7
–37.3	–102.4	–106.1	–103.2	–103.3	–111.0
–42.4	–96.2	–100.7	–106.5	–117.1	–116.6
–47.2	–97.3	–108.7	–110.1	–116.7	–115.5
–52.0	–101.7	–108.7	–118.0	–122.2	–114.0
–57.0	–104.8	–123.8	–109.6	–114.4	–111.4
–61.9	–121.1	–104.5	–102.9	–109.0	–122.3
–66.7	–96.8	–106.0	–109.8	–116.2	–117.7
–72.4	–117.1	–130.5	–122.4	–131.9	–128.7
–77.3	–120.9	–122.0	–125.7	–125.3	–127.2
–82.1	–117.8	–119.0	–125.6	–137.8	—
–87.3	–116.1	–129.7	—	—	—
–92.3	–124.2	—	—	—	—
–96.6	–134.5	—	—	—	—
–100.1	—	—	—	—	—

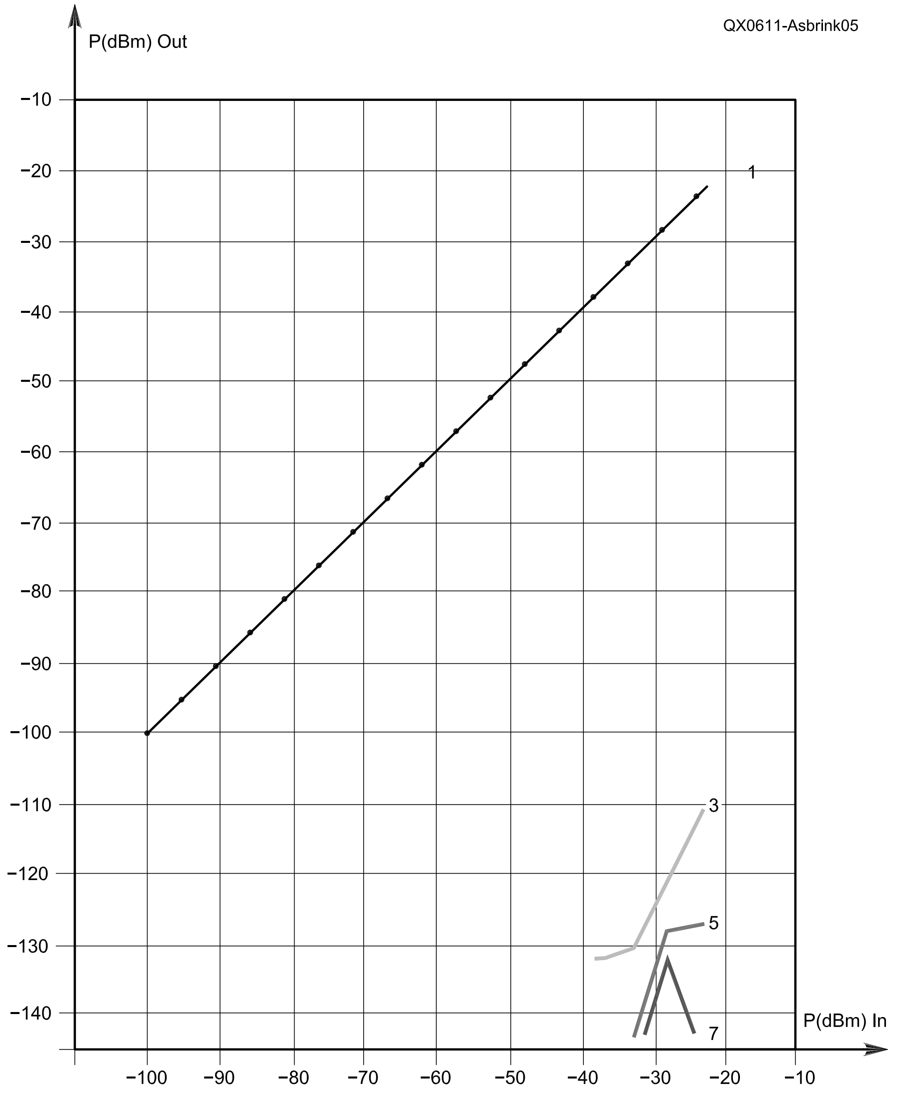

Figure 5 — With white noise used for dithering, the false signals are reduced significantly.

+40 dBm, which would call for a class A amplifier capable of delivering several watts. Such an amplifier with enough gain to place the antenna noise floor at –95 dBm in 500 Hz bandwidth would give a spur-free dynamic range of 90 dB at the same time as the noise floor is allowed to be lifted 15 dB by the preamplifier chain. For a 144 MHz weak signal operator this is very hard to accomplish in any other way, since the increase in the noise floor of about 15 dB that is necessary for a really low system noise figure is associated with a loss of dynamic range by about 15 dB in a conventional receiver.

Test Procedures

The standard procedure for measuring the two-tone, intermodulation-free dynamic range, used for example at the ARRL Lab, is to gradually increase the test signal until the third-order intermodulation signal equals the noise floor. While adequate for conventional analog receivers, although sometimes technically extremely difficult (on really good receivers), this procedure does not give a valid result for a digital radio like the SDR-14. Therefore, a different procedure should be adopted. It would give identical results as the old procedure on analog receivers but it would give a true figure of merit for digital radios. Rather than measuring what level is required for getting IM3 equal to the noise floor, one should measure the largest difference (in dB) between the test

Table 3

Power in dBm for signals of order N

N:	*1*	*3*
	–21.7	–105.8
	–26.7	–121.8
	–31.7	—

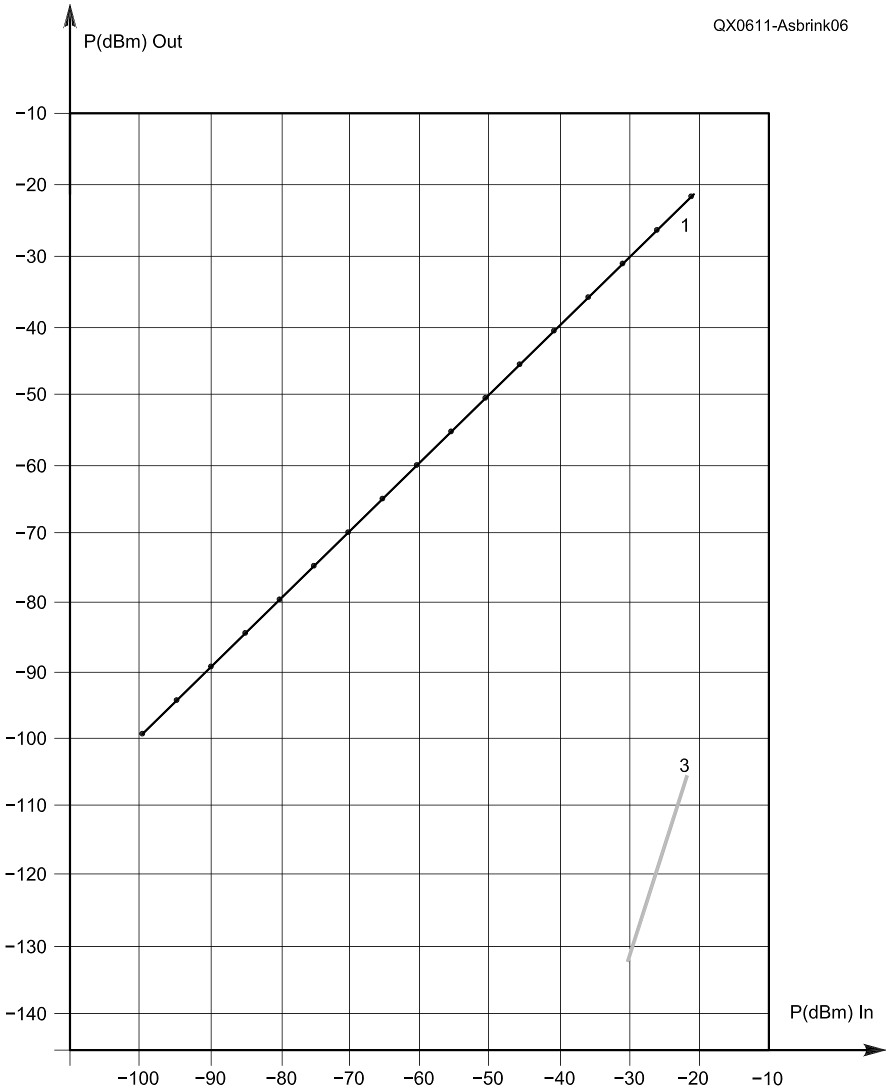

Figure 6 — With a frequency modulated carrier used for dithering, the false signals created by the A/D converter are weaker than the third-order intermodulation of the built-in preamplifier.

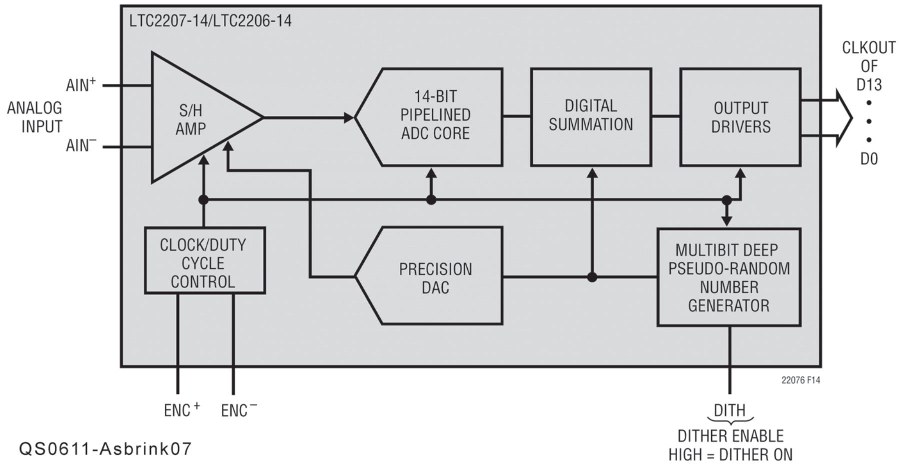

Figure 7 — The dithering used in LTC2206/2207. When dithering with noise, one normally has to incorporate filters that prevent any noise within the desired passband from reaching the A/D converter. This chip adds the same noise with opposite sign to the input and to the digital output. The cancellation means that the dithering noise will not be present in the output regardless of frequency, without any filters. (Copyright Linear Technologies, Inc, 2006, used with permission.)

tones and the intermodulation product. It will be close to saturation of the A/D converter on the SDR-14, while it will be at the noise floor for an analog receiver. Obviously the digital radio might need an RF amplifier to lift the external noise floor to the IM3 level observed in the test.

Both analog and digital radios need attenuators or amplifiers to place the external noise at the optimum level in order to get the maximum performance. Using an analog receiver with a very low noise figure on 40 meters in evening times without an attenuator will cause similar interferences as using a digital radio without an amplifier during the same circumstances!

The Future of Digital Receivers

The two causes of interference on intermodulation frequencies, A/D converter non-linearities and interference from the digital data lines, can be largely decreased by smart chip design. The LTC2207 from Linear Technology uses a random number generator that drives a D/A converter that adds noise to the input signal. The same noise is then subtracted at the digital side, as illustrated in Figure 7, taken from the data sheet.

The following excerpt from the LTC2207 data sheet illustrates the problems with the data bus:

"Interference from the ADC digital outputs is sometimes unavoidable. Interference from the digital outputs may be from capacitive or inductive coupling or coupling through the ground plane. Even a tiny coupling factor can result in discernible unwanted tones in the ADC output spectrum. By randomizing the digital output before it is transmitted off chip, these unwanted tones can be randomized, trading a slight increase in the noise floor for a large reduction in unwanted tone amplitude. The digital output is "Randomized" by applying an exclusive-OR logic operation between the LSB and all other data output bits. To decode, the reverse operation is applied; that is, an exclusive-OR operation is applied between the LSB and all other bits.

Leif was born in 1944 and licensed in 1961. He holds a PhD in physics and worked with research on molecular physics for 15 years at the Royal Institute of Technology. Since 1981, he has been running his own company developing various electronic products. He is the inventor of the magnetic intermodulation EAS system now owned by Checkpoint. Leif is essentially retired and works mainly with Amateur Radio related technical projects.